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Geometrical Variations Management 4.0: towards next Generation Geometry Assurance

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Abstract

Product realization processes are undergoing radical change considering the increasing digitalization of manufacturing fostered by cyber-physical production systems, the internet of things, big data, cloud computing, and the advancing use of digital twins. These trends are subsumed under the term “industry 4.0” describing the vision of a digitally connected manufacturing environment.
The contribution gives an overview of future challenges and potentials for next generation geometry assurance and geometrical variations management in the context of industry 4.0. Particularly, the focus is set on potentials and risks of increasingly available manufacturing data and the use of digital twins in geometrical variations management.

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Keywords: Industry 4.0; Digital Twin; Geometry Assurance.

Nomenclature

CAD	Computer-Aided Design
CMM	Coordinate Measuring Machine
CPS	Cyber-Physical System
FEA	Finite Element Analysis
IoT	Internet of Things
MBD	Model-Based Definition
OEM	Original Equipment Manufacturer
PDM	Product Data Management
PMI	Product Manufacturing Information

1. Introduction

Geometrical variations management and geometry assurance describe all efforts related to controlling and minimizing the effects of geometrical part deviations on the product quality throughout the whole product life-cycle particularly considering inevitable variations in manufacturing, assembly, and joining processes. However, product realization processes are currently undergoing radical change considering the increasing digitalization of manufacturing fostered by cyber-physical production systems, the internet of things, big data, cloud computing, and the advancing use of digital twins. These trends are subsumed under the term “industry 4.0” as a vision of a digitally connected manufacturing environment.

Motivated by these trends and developments, the contribution gives an overview of future challenges and potentials for next generation geometry assurance and geometrical variations management in the context of industry 4.0. Particularly, the focus is set on potentials and risks of increasingly available manufacturing data and the use of digital twins in geometrical variations management.

The paper is structured as follows. In the next section, a brief background regarding the established understanding of geometrical variations management and geometry assurance is discussed. Moreover, the vision of industry 4.0 and the current trend of increasing digitalization in manufacturing is briefly highlighted. After that, a definition of next generation geometry assurance and geometrical variations management 4.0 is derived. Furthermore, the benefits and challenges of

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increasing digitalization in geometry assurance are discussed. Finally, a conclusion and an outlook are given.

2. Background

Before addressing the main issues of the paper, this section is to provide the reader with important background regarding geometrical variations management, geometry assurance, industry 4.0, and the current trend of increasing digitalization in manufacturing.

2.1. Geometrical Variations Management and Geometry Assurance

Even though modern manufacturing processes achieve steadily increasing accuracy, it is widely acknowledged that geometrical deviations can be observed on every physical artefact. Indeed, these geometrical deviations have various process-related sources and are ubiquitous throughout all stages of the physical product realization process. Furthermore, they have distinct effects not only on the product function, but also on the perceived quality of products [1, 2] and their economic and environmental sustainability [3]. Moreover, often these geometrical part deviations add up with further deviations caused by physical phenomena, such as wear, thermal expansion, or part deformations [4, 5] and hence further deteriorate the product quality during use. Consequently, there is a strong need for companies to manage these geometrical deviations throughout the whole product life-cycle [6, 7].

Prior to the first industrial revolution, when products were made by artisans and the different activities and stages of product origination from design, to manufacturing, assembly, and testing were physically and personally unified [8, 9], the management of geometrical part deviations was usually performed by fitting parts to their mating parts [10], thus manually reducing the "relative"' deviations between parts for every single entity. Since then, triggered by the introduction of interchangeable parts in the 18th century, i. a. the ambition for efficient fabrication of physical artefacts in mass production, the increasing product complexity, and the diversification of customer needs, have led to a disruption of design, manufacturing, assembly, and inspection, to an increasing specialization of these disciplines, and particularly to a dichotomy between design and manufacturing [8]. Even today, this disruption becomes apparent in modern series manufacturing chains, which are strongly based on the concepts of total or partial part interchangeability, process independence, and external procurement [9]. Thus, industry is facing the current situation, in which many departments and different actors from product design, to manufacturing, inspection, assembly, and testing, are involved in the geometrical variations management process.

In this context, geometrical variations management "can be understood as the set of activities related to controlling geometrical deviations and their effects on the product quality throughout the product life-cycle" [11], while geometry assurance can be described with some similarity to this "as a number of activities, all contributing to minimizing the effect of geometrical variation in the final product" [7]. Geometry assurance activities can be found in all the different phases of the product realization loop [7] (see Fig. 1).

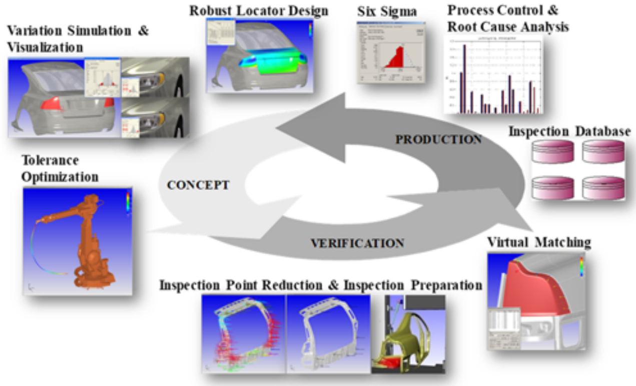

Fig. 1. Geometry Assurance Activities according to [7].

2.2. Industry 4.0 and the increasing Digitalization in Manufacturing

The vision of industry 4.0, also depicted as the fourth industrial revolution, aims at establishing a close link between industrial manufacturing and modern information and communication technologies. By employing cyber-physical (production) systems and their connection across complex value-added chains, efficiency improvements in manufacturing as well as increasing flexibility regarding fluctuating customer and market requirements should be realized [12]. A key concept and an important enabler of industry 4.0 are cyber-physical systems (CPS), which connect the digital and physical worlds. CPS "are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the Internet" [13]. In addition, the internet of things (IoT) enables the continuous information transfer between humans, machines, companies, systems, and sensors. Based on the steadily available data, digital twins (sometimes also called "virtual twins") link theoretical knowledge with data from practice in real time and take on controlling whole value-added chains [14].

The sketched development of increasing links and connections between company-internal departments, such as product design, engineering design, manufacturing, and logistics as well as company-external partners, such as suppliers, sales partners, and customers is predominantly welcomed due to the benefits for increasing the customer value as well as the productivity. However, established business processes are to adapt to the technological progress and the new environment to be able to fully exploit the benefits of industry 4.0. More particularly, the current trend of increasing digitalization in manufacturing is about to dramatically change established geometry assurance and geometrical variations management processes. Thus, the aim of this paper is to address the potentials as well as the fundamental challenges related to next generation geometry assurance and to carve out important research issues for the next years.

3. Geometrical Variations Management 4.0 and Next Generation Geometry Assurance

Based on the provided background, it can be seen, that industrial revolutions have ever since changed the way and importance of activities related to controlling and minimizing the effects of geometrical deviations on the product quality. Thus, it is indisputable that also the fourth industrial revolution will strongly affect next generation geometry assurance and will inevitably lead to geometrical variations management 4.0. The next sections are to explore these developments and to highlight some of the most promising potentials as well as fundamental challenges related to this domain.

3.1. Understanding and Definition

Based on the definitions of geometrical variations management and geometry assurance, which cover all activities related to controlling and minimizing the effects of geometrical deviations on the product quality throughout the product life-cycle, as well as the common understanding of industry 4.0, which stands for the vision of a comprehensive efficiency increasing and value-adding digitalization in manufacturing, geometrical variations management 4.0 can be understood as *a comprehensive digital process supported by various computer and software tools aiming at controlling and minimizing the effects of geometrical deviations*. In this context, the different process steps are fully connected by modern information and communication technologies allowing a continuous and unambiguous flow of information throughout the whole product life-cycle and also between physical parts and products and their digital twins (Fig. 2).

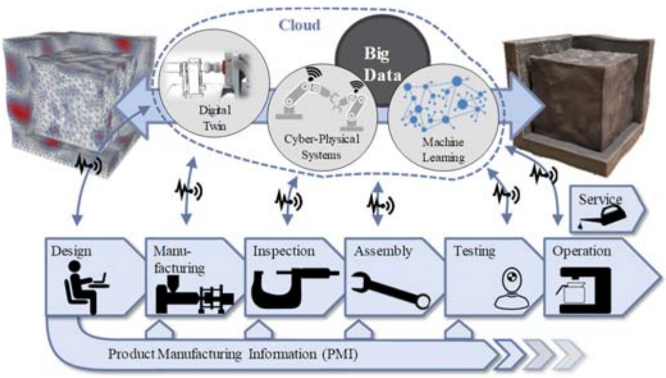

Fig. 2. Geometrical Variations Management 4.0 acc. to [14].

3.2. Enablers of next Generation Geometry Assurance

Based on the definition of next generation geometry assurance, this section is to highlight some of the most important enablers for geometrical variations management 4.0 as illustrated in Fig. 3.

Data Collection

Next generation geometry assurance strongly builds on the steady availability of data from manufacturing, assembly, test, and operation. Consequently, a main enabler of geometrical variations management 4.0 are possibilities for data collection and data acquisition. In this context, cyber-physical (production) systems provide the link between the real and the virtual worlds in manufacturing by incorporating data collection and sensor technologies [13, 15]. Beside this, even more advanced scanning technologies allow the quick and vast collection of large data sets from physical parts as well as from their surroundings [16]. In addition, "smart products" offer increasing possibilities for data collection during operation since they are equipped with sensor technology and are steadily connected to the internet [17]. This data can be used to assess and predict the load and operating conditions of products during use.

Data Transfer

Driven by these new possibilities for data collection, there arises also a strong need for transferring the captured data to all the different actors in geometry assurance. The internet (of things) but also new approaches to product lifecycle management are to allow the quick and easy access to these large data sets considering the characteristics of "big data" [18]. Moreover, increasing data storage and transfer capabilities enable the data usage in geometry assurance. However, in this context, the issues of data quality, data validity, and data security grow in importance. Furthermore, open interfaces and standardization activities are required in order to provide interoperability between the different systems used for data collection, data transfer, and data processing [19].

Data Processing

Once the data from different steps of the product realization process are collected and transferred, these data sets have to be processed. For this purpose, more sophisticated methods for data analytics, such as machine learning, meta-modelling, and dimensional reduction [20-22], as well as for cloud computing and data visualization are required.

Beside this, increased computer power, faster algorithms, and more efficient optimization routines are to allow simulation models to be used in-line with real-time data as so-called "digital twins" [21, 23, 24]. In this context, the vision of a digital twin was introduced by NASA for safety and reliability optimizations [25, 26]. In this context, the digital twin often refers to a comprehensive physical and functional description of a component, product or system, which includes more or less all information which could be useful in the current and subsequent lifecycle phases [27, 28].

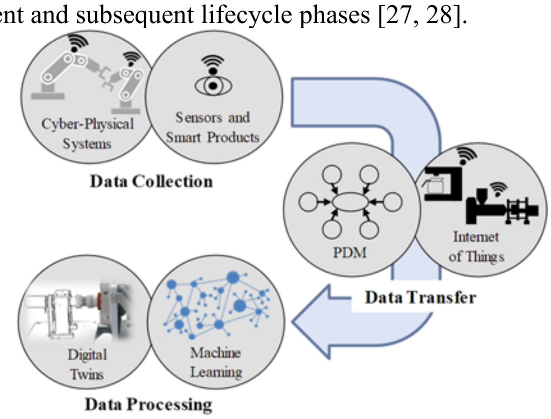

Fig. 3. Main Enablers of Geometrical Variations Management 4.0.

3.3. Potentials of next generation Geometry Assurance

Improved Simulation Models and Digital Twins

Due to the complexity of modern manufacturing and assembly processes, the final geometrical quality of a large assembly depends upon a vast number of different parameters. In this regard, for example the part variation itself relates to the manufacturing process and the material properties, while on assembly level, the assembly and joining process need to be modelled. This includes number, position, and geometries of locators and supports as well as their variation and sequence. It also includes the variation related to the joining process such as forces, sequences, and the effect of heat. In Fig. 4, a number of factors affecting the geometrical quality of a subassembly or a product are listed [29]. All these factors that affect the real outcome should of course also be included in variation simulations.

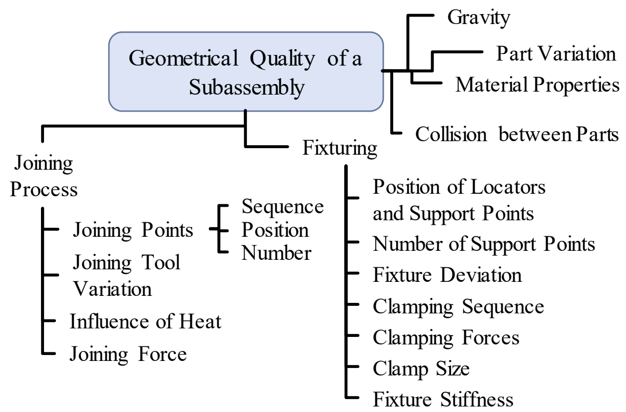

Fig. 4: Factors affecting geometrical quality acc. to [29]

To realize the concept of a digital twin for geometry assurance, all these parameters need to be considered in the simulation model, which must therefore be able to realistically model and simulate 1) the geometrical deviations on individual parts, 2) the variation propagation in an assembly and 3) the effect from joining. To be able to run the simulation model as a digital twin, i. e. using real-time data to simulate and control the manufacturing and assembly process, fast simulation models are needed. While full simulation models can be used for development and optimization in early phases, simplified meta-models of the full simulation model are required for use in real-time during production. Alternatively, scanning of parts can be done already at the supplier. Then there will be time to run simulation models to evaluate the best possible process settings before assembly, taking place at the OEM. Moreover, the realization of a digital twin for next generation geometry assurance requires a strong conceptual basis and a comprehensive reference model as highlighted in Fig. 5, which serves as a template for the implementation of digital twins for specific applications while ensuring important model properties, such as model scalability, interoperability, expansibility, and fidelity [23].

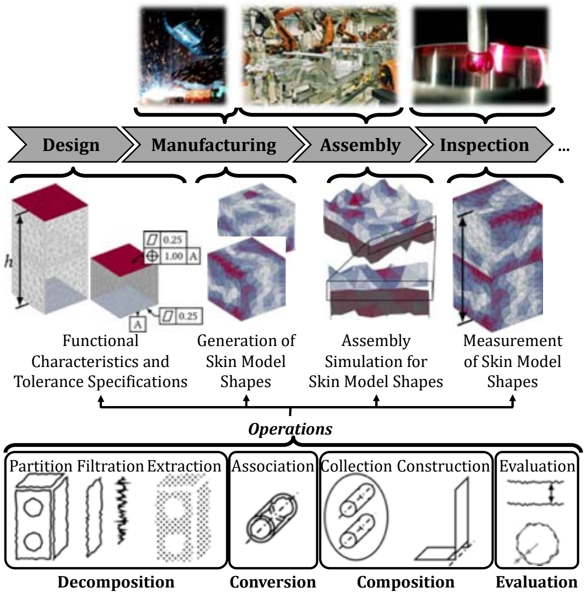

Fig. 5: Comprehensive Reference Model for the Digital Twin acc. to [23]

Once established, digital twins for geometrical variations management can be used for identifying root causes of geometrically related variations in full production. Using inspection data on assembly level allows to identify problems in the assembly fixtures. The relationship between input and output established in the simulation model is then reused for this purpose and variations can be divided into variation caused by the assembly fixtures and other variation [30].

In addition, loads and operating conditions obtained from smart products can be integrated in such digital twins and sophisticated variation simulations can be performed considering physical phenomena, which interact with geometrical deviations introduced in part manufacturing and assembly and further influence the product quality during use [31, 32, 33]. Based on the steady transfer of operating conditions, also maintenance intervals and repair procedures can be triggered [34].

Until recently, simulation has been used extensively in the design phase with estimated or historical data as input. However, future abilities to scan and analyze geometries of parts and subassemblies in real-time will support geometry assurance with new possibilities to adjust the assembly process and to compensate for geometrical deviations of incoming parts. Fig. 6, shows a first implementation of this vision in the self-compensating assembly line including scanning of parts, sorting, matching, trimming, sequence optimization, scanning of subassembly and feed-back to the system. The individual steps are described in detail in [24].

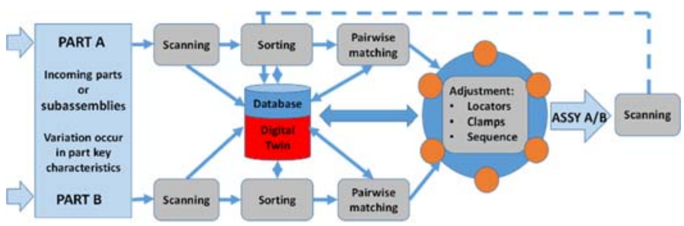

Fig. 6: Self-compensating assembly line acc. to [24]

Beside later design and production stages, increased availability of scan data will also support early design phases. Variation simulation can be performed, and visualized, using more realistic data for part and assembly variation. Typically, scan data from similar parts manufactured under similar conditions are morphed onto the new geometries to represent the characteristic "process signature" [35]. Visualization of the effect of variation with high degree of realism can then be done by adding lightning, shadows, textures, material properties etc [36]. The visual sensitivity of the product can then be judged with respect to geometrical variation long before production takes place and unnecessary late changes can be avoided.

Improved Understanding of Process and Quality Relations

The availability of large data sets coupled with the employment of digital twins, sophisticated simulation models, and data analytic approaches allows to identify unknown dependencies between process variables and the product quality. In this context, next generation variations management will allow to realistically consider characteristic manufacturing signatures and to perform process-oriented tolerancing [37].

These approaches will thus allow gaining an improved understanding of the effects of manufacturing, assembly, and operating parameters on the product quality and will hence strongly support the decision making in product and process design [30, 38].

The knowledge about the dependencies between process variables and product quality will strongly affect inspection planning and put forward optimization methods dedicated to simultaneously minimizing measurement cost and inspection uncertainty cost [39, 40].

Beside this, the improved understanding of relations between process characteristics and product quality will allow more efficient process monitoring procedures and change the established means of process monitoring [41] and inspection optimization [42]. Furthermore, next generation geometry assurance and the increasing interconnectedness of manufacturing and inspection machines will allow for even more improved techniques of adaptive inspection [43].

Continuous Digital Thread in Geometry Assurance

In return of the data flow from manufacturing, assembly, testing, and operation to design, the increasing digitalization of all stages in product development will also allow a continuous digital thread from design to all downstream activities in geometry assurance. In this regard, product specifications and product manufacturing information (PMI), which are increasingly specified via model-based definition (MBD) to the 3D master product model [44, 45], will be directly transferred to manufacturing and inspection machines. This will eliminate the need for time-consuming and error-prone manual copying of specifications annotated on technical drawings to the control of coordinate measuring machines and machining centers.

Business Models

Cyber-physical systems, digital twins and IoT will open up for new ways of collaboration between OEMs and suppliers. Digital networks will allow a more distributed way of collaboration and offer the ability to work more efficiently with small suppliers, specialized in different areas, or located close to the customer. This will open up for new business models.

3.4. Challenges and Risks

Development of Realistic and Real-Time Simulation Models

The availability of large data sets from manufacturing and inspection dictates the development of new and more mature simulation models that can be used to process the available data in real time and with better result accuracy. For next generation geometry assurance, this requires particularly the development of assembly simulation models that allow the realistic consideration of form deviations and process signatures in the prediction of the assembly behavior [46, 47].

New Manufacturing Processes and Engineering Materials

New evolving manufacturing paradigms, such as additive manufacturing, require novel methods and tools for the geometry assurance [48, 49]. In this regard, advanced approaches for the deviation modelling [50] as well as for the integration of manufacturing process simulations in the geometry assurance process are crucial. Beside this, also new materials, such as short- and long-fiber reinforced thermoplastics, challenge geometrical variations management 4.0. In this context, new simulation and assessment methods are to be integrated in variation simulation workflows to enable the full exploitation of lightweight design potentials considering product manufacturability and product quality [51, 52].

Increasing Complexity

Digital networks and new business models may increase the flexibility and provide benefits regarding the efficiency and productivity, but also increase the complexity of the system. The need for good control of the process will become necessary as more and more will be distributed among many actors.

By using digital twins to perform real-time updates of the process parameter settings, a sensitive system is created. The process is changed over time, leading to an interlinked system where it is difficult even for experienced engineers to get an overview of different causes of variation. Instead, one has to rely on the simulation model which puts high requirements on the reliability and validity of the model (discussed in Sec. 3) and the input data.

Data Quality

To secure the data quality and validity it is extremely important to secure that the right data is used. In this context, it means that the information content in the inspection data must be high. For coordinate measuring machines (CMM) data, the right inspection points must be chosen to maximize the information content in data. For scan data, limited resources for storing and, not least, handling and analysis of data might create a need for reduction of scan data and point clouds. Also here, it is important to maximize the information in the stored data.

To find the information carriers, i.e. the inspection data containing the maximum information, a model-based or a data-based approach can be utilized. In the model-based approach, the digital twin is utilized for a sensitivity analysis, where unit disturbances are applied to all input tolerances and other input parameters. The outputs resulting from each disturbance are registered and sensitive areas can be identified. To maximize the information content inspection data covering those areas should be utilized and stored.

In the data-based approach, previous inspection data can be utilized and correlations among inspection data can be utilized to form clusters. From each cluster, one representative can be chosen and then, only the representatives are measured or stored. In that way the amount of data is reduced but most of the information remains [20].

Another issue related to data quality is the repeatability of the used inspection device, which should be included as an input to the digital twin [53].

Big Data Issues

Challenges with Big Data are often referred to using the V-model [54] and classified within Volume, Velocity and Variety. Challenges for handling Big Data for geometry assurance are particularly:

- Volume: how to reduce the stored set of data [21], particularly for large sets of measured points.
- Velocity: Relates to both capture speed and analysis time for those large data sets in measurement and variation simulations.
- Variety: There might be different types of data that need to be combined, for example both pure inspection data and metadata.

The volume challenge is discussed above. The velocity of scanning is an area of research showing major progress recently. In [55], a photogrammetry based in-line inspection system is proposed. It is reported that a point cloud can be generated from a captured image of a part within 30 seconds. This point cloud can then be fitted to the nominal geometry in milliseconds [55]. This technology seems promising and should be possible to utilize to feed a digital twin for geometry assurance.

It is also important that the inspection data shows the actual behavior of the part. In many cases, an over-constrained locating scheme is used during inspection. Then the actual shape of the part cannot be captured, making it difficult to achieve correct spring back predictions in the variation simulation. In [56] a 3-2-1 locating scheme for inspection is suggested, but the paper also discusses how this inspection data virtually can be transformed into an over-constrained shape, making the inspection data useful for both variation simulation and other analyses.

Beside these three main challenges, further issues arise in the context of big data, such as data veracity and data volatility.

However, the data used both to feed simulation models and to perform root causes analysis must be rich and valid. Data must, besides geometrical deviations, also contain information about the process status during manufacturing of the part and/or subassembly. Examples of such metadata can be date, time, operator, batch number, parameter settings during stamping and assembly etc. In order to achieve this, data sanitation methods and data processing techniques considering data sharing agreements and data quality attributes are required [57].

Moreover, data variety, particularly in the context of inspection and verification, has to be tackled by data fusion techniques (see e.g. [58]). For this purpose, more sophisticated approaches need to be developed, which allow the fusion and combination of different types of data from process monitoring, part inspection, and performance testing.

Data Flow and Security

In a fully digitized process for geometrical variations management 4.0 and next generation geometry assurance, all models and data such as CAD models, FEA meshes, inspection data etc, needs to be handled by the PDM system and correctly fed to the process activities in the right moment. A continuous digital thread, supporting the activities in Fig. 2, needs to be established. This will include the interplay between OEM and suppliers and it will also allow for a closed-loop geometrical variations management [59].

Moreover, while ensuring the data to be up-to-date, PDM systems have to restrict data access to authorized users in order to prevent data theft and confidentiality issues.

Education for Geometrical Variations Management 4.0

Beside the technical issues related to next generation geometry assurance, also the provision of adequate curriculums and educational programs for engineers of tomorrow is an important challenge. In this context, it is not only a necessity for modern tolerancing engineers to share the ability to fluently communicate in the tolerancing language offered by modern GPS standards and to have basic knowledge in statistics, production engineering, and design, but also to be familiar with modern IT technologies, such as simulation tools, machine learning algorithms, and data analytics methods. The diversity and requirements of these various topics need to be carefully integrated in modern teaching concepts.

4. Conclusion and Outlook

The increasing digitalization becomes not only apparent in our daily lives, but also puts established product realization processes under immense pressure. In this context, particularly geometrical variations management and geometry assurance, which comprise all efforts related to controlling and minimizing the effects of geometrical part deviations on the product quality, will undergo radical change during the next decades. This change is fostered by cyber-physical production systems, the internet of things, big data, cloud computing, and the advancing use of digital twins in geometry assurance.

Motivated by this, the present contribution provided a first definition of next generation geometry assurance (geometrical variations management 4.0), highlighted its main enablers, outlined the main potentials offered by the increasing digitalization in geometry assurance, and discussed some challenges related to this development. In this regard, the main aim of the paper is to further encourage and stimulate the research efforts in this domain, which are already visible in ongoing research projects.

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